

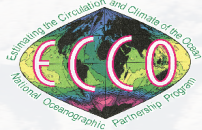
Adjoint modeling in cryosphere

Patrick Heimbach

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<http://www.ecco-group.org>

<http://mitgcm.org>

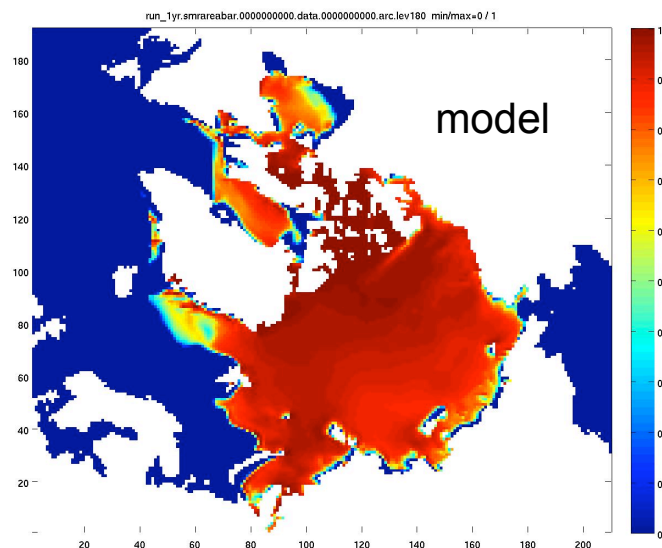
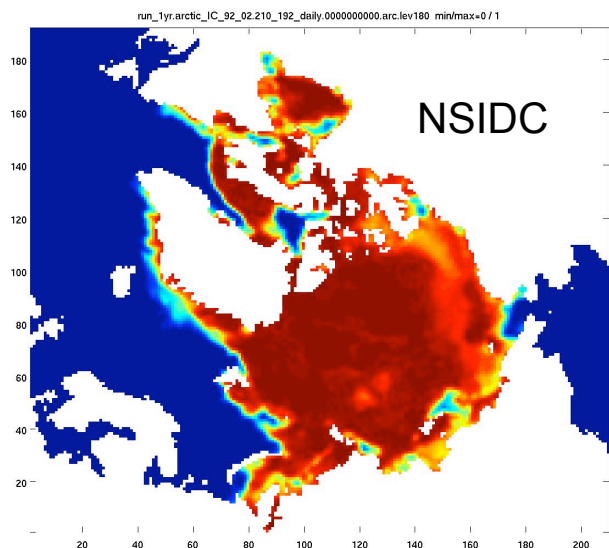
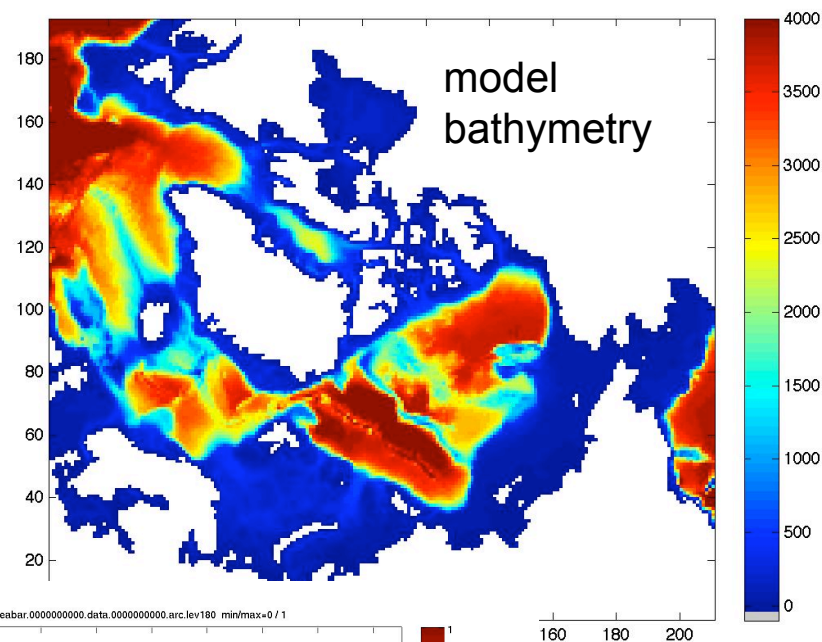


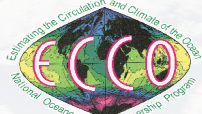
The MIT sea-ice model (MITsim)

- **Thermodynamics**
 - Based on *Zhang & Hibler, 1997*
 - Two-category, zero-layer, snow melting and flooding (*Semtner, 1976; Washington & Parkinson, 1979*)
 - Sea ice loading and dynamic ocean topography (*Campin et al., in press 2008*)
- **Dynamics**
 - Two solvers available for viscous-plastic (VP) rheology:
 - Line Successive Relaxation (LSR) implicit (*Zhang & Hibler, 1997*)
 - Elastic Viscous-Plastic (EVP) explicit (*Hunke & Dukowicz, 1997*)
 - Both ported on C-grid for use in generalized curvilinear grids
 - Various advection schemes available
- An **exact** (with respect to **tangent linearity**) adjoint,
 - generated via automatic differentiation tool TAF

Present Arctic configuration

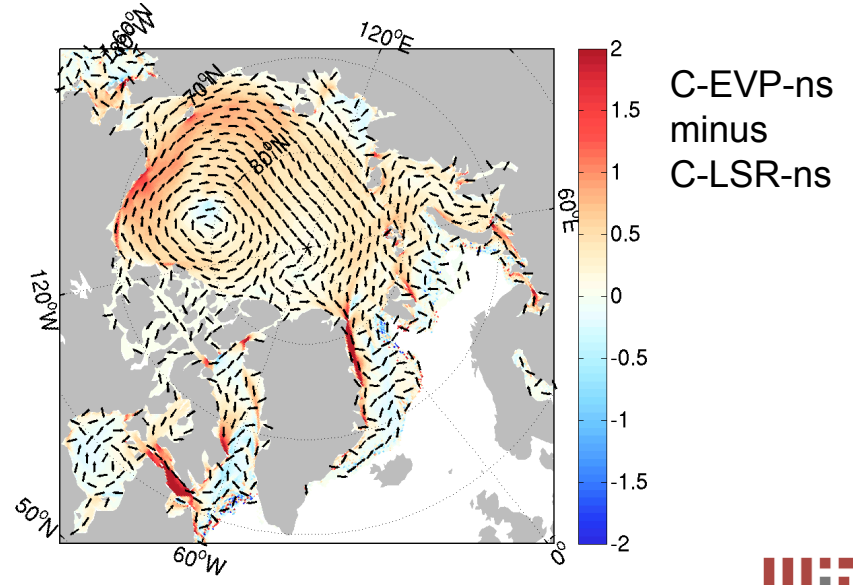
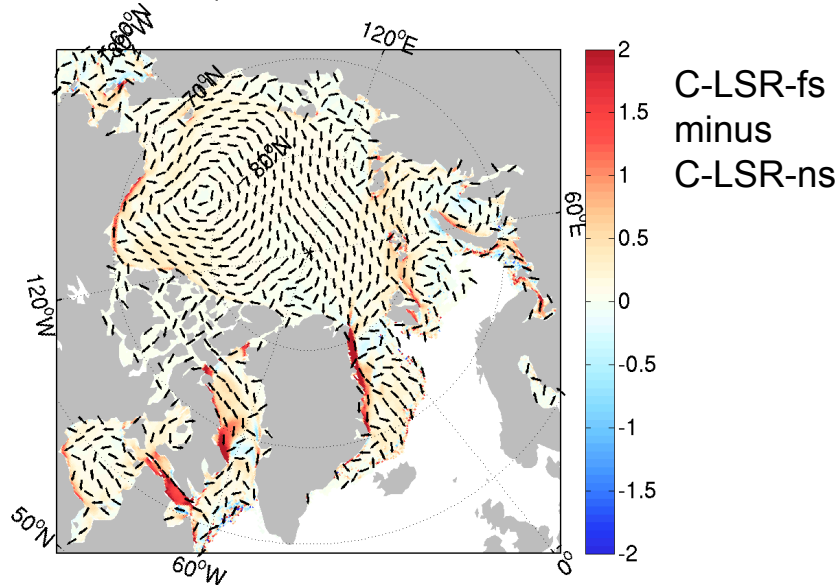
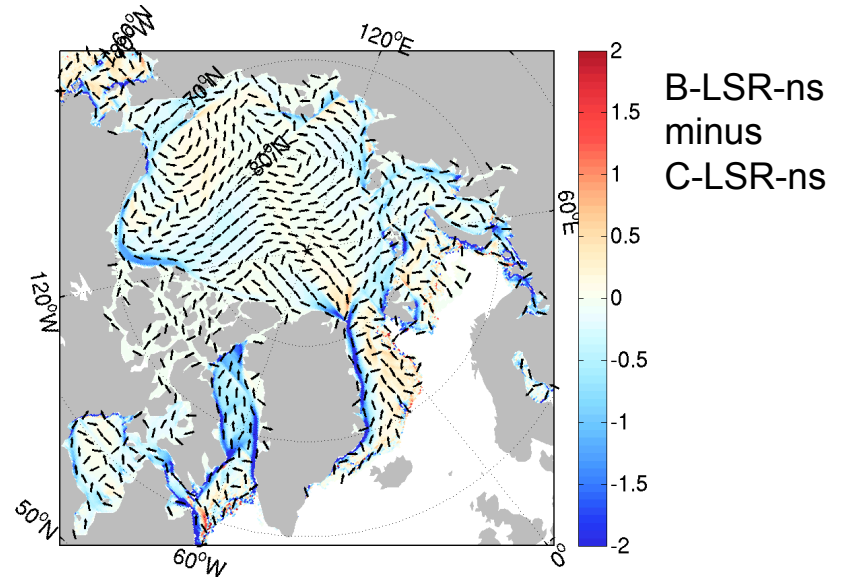
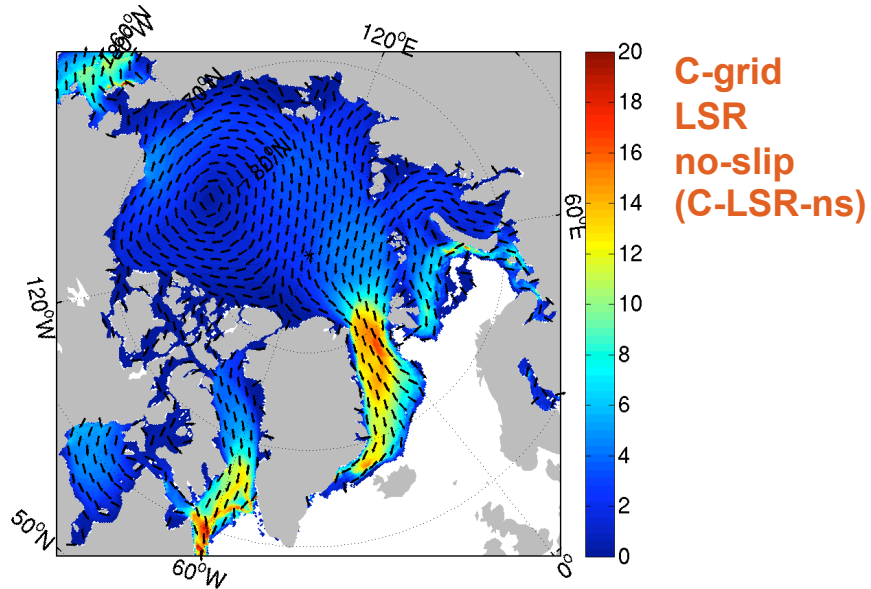
- Coarsened Arctic face of the ECCO2 global cubed sphere (from ~18 km to ~36 km horizontal resolution)
- Underlying ocean model uses various parameterization schemes (KPP, GM/Redi)
- 6-hourly forcing via NCEP/NCAR atmospheric state, converted to open-ocean air-sea fluxes via Large & Yeager (2004)
- Sea-ice dynamics via LSR on C-grid
- Adjoint runs on 80 processors (e.g. on IBM SP or SGI Altix)

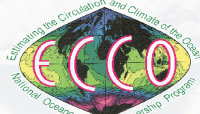




The forward model - configuration sensitivities

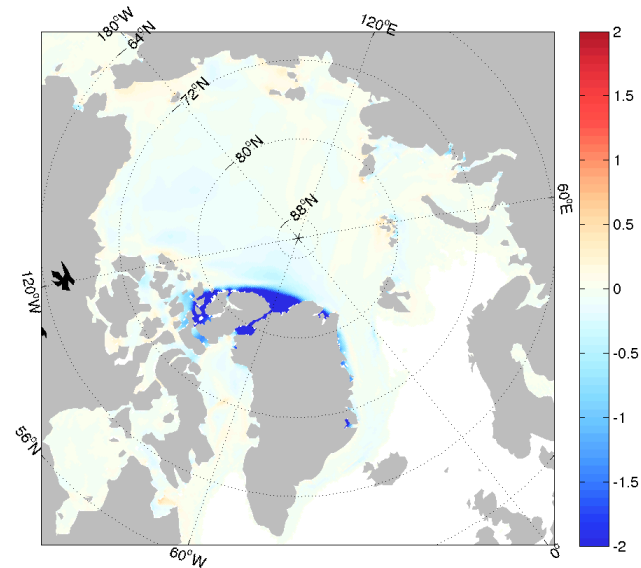
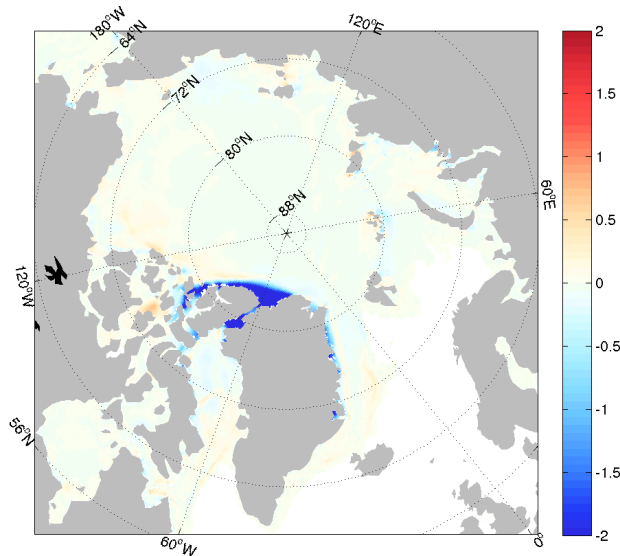
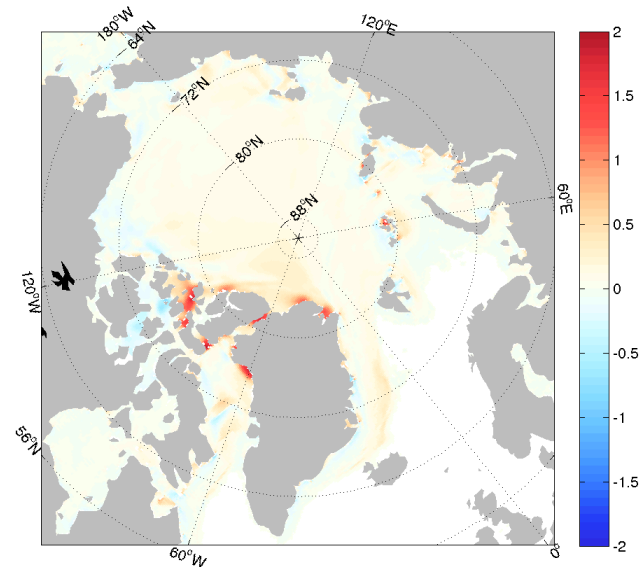
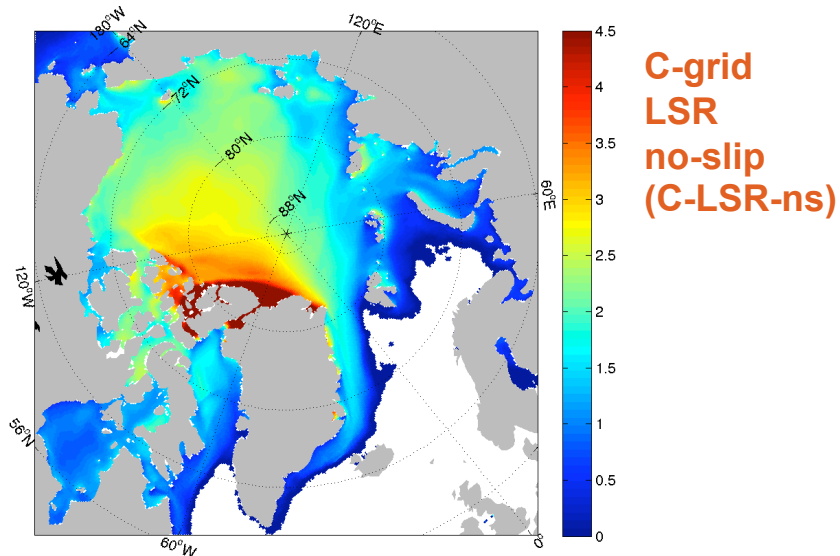
Ice drift velocities

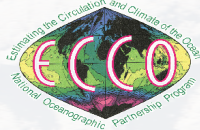




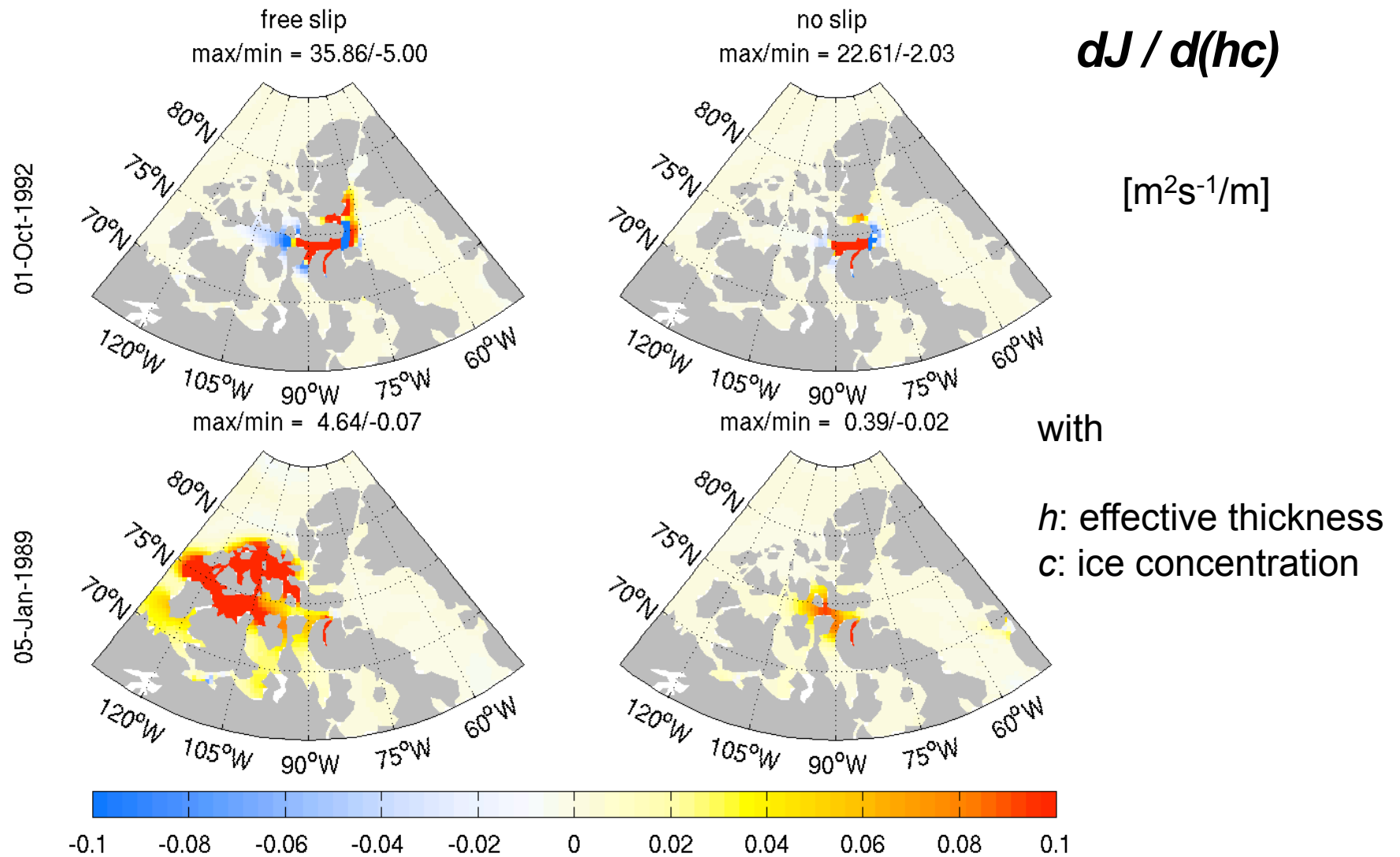
The forward model - configuration sensitivities

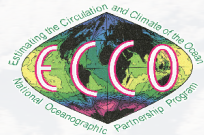
Effective ice thickness





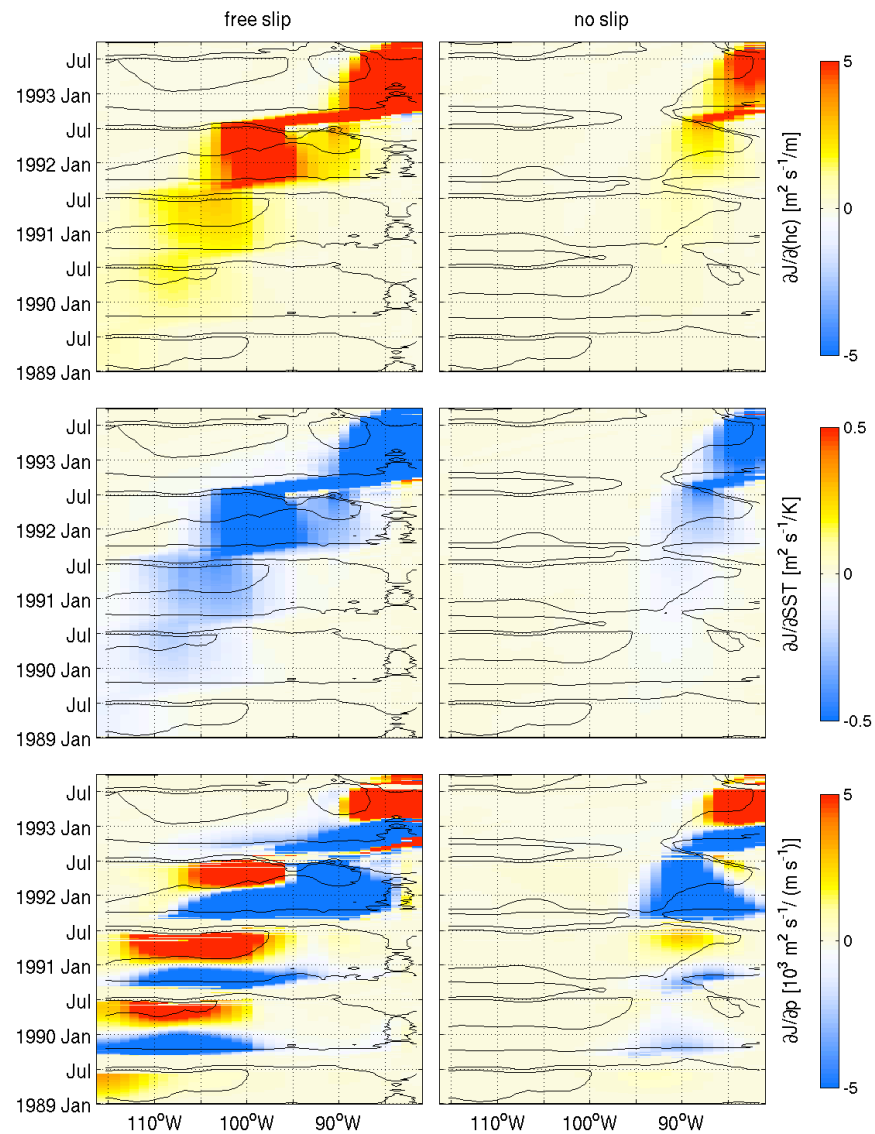
Adjoint sensitivity of solid freshwater transport through Lancaster Sound

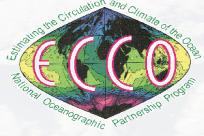




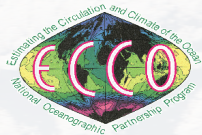
Adjoint sensitivity of solid freshwater transport through Lancaster Sound

Hovmueller diagrams of adjoint sensitivities





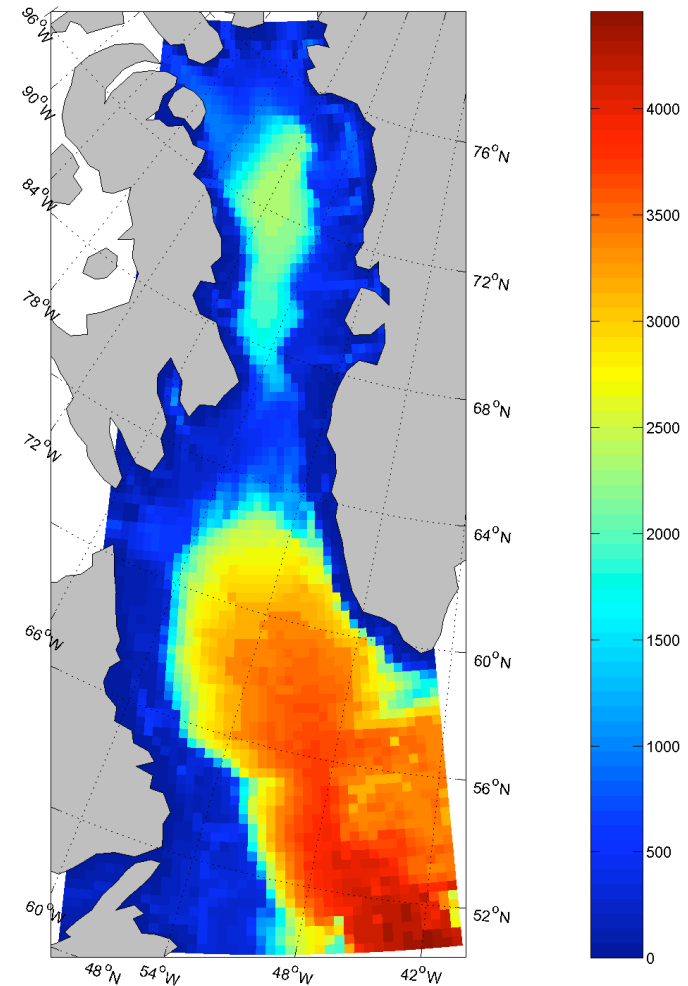
Another one: Sea-ice export through Fram Strait



Sea-ice state estimation in a limited-area setup of the Labrador Sea (I)

- MITgcm with Curvilinear Grid
 - 30 km x 30 km → 30 km x 16 km
 - 23 vertical levels
- 1.5 Layer dynamic-thermodynamic sea ice model with snow
 - Stress-Strain rate based on Hibler (1980) ellipse
- Open boundaries
 - Weak sponge layers at Southern and Eastern edges
- Resolved Labrador and Greenland Shelves
 - Critical for sea ice production and advection
 - Important for boundary currents
- Computational efficient
 - Parallel: 1 real hr/ simulated year on 6 nodes

Ian Fenty (Ph.D. thesis)



Bathymetry of model domain.
Each distinct pixel is on cell

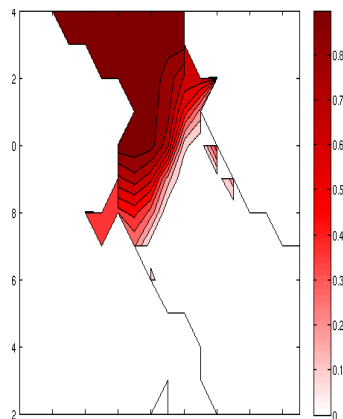
Sea-ice state estimation in a limited-area setup of the Labrador Sea (II)

Correct propagation of adjoint variables

Cost function (J) = Week 52 Integrated ice area

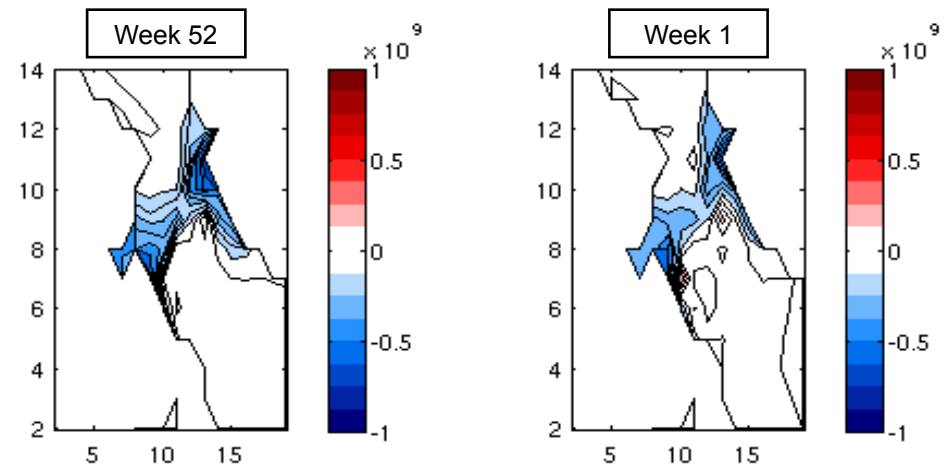
Demonstration of influence of distribution of heat anomalies in space and time, $dJ(x,T)/dT$

- Results are of correct sign (additional heat decreases the week 52 ice concentration)
- Influence of SST anomalies are reduced further back time. Anomalies far in past are damped by the atmosphere.
- Subsurface influence persists and propagates upstream along the model's boundary currents (closed boundaries in this demonstration)

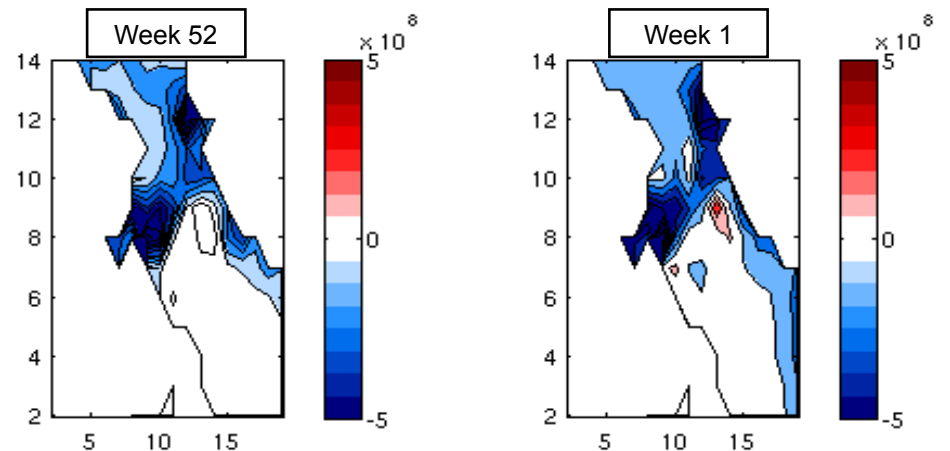


Ice Concentration at Week 52

dJ/dT (Surface)



dJ/dT (300 m)



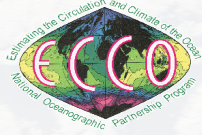
Ian Fenty (Ph.D. thesis)

Evolution: from water to land ...

- Whilst standing on the Fennoscandian ice sheet, we thought...
- Adjointns should be useful for ice sheet modeling and estimation

➔ *Heimbach & Bugnion, 2008:*
Equilibrium sensitivities of the Greenland ice sheet inferred from the adjoint of the three-dimensional thermo-mechanical ice sheet model SICOPOLIS
(submitted to *Annals of Glaciology*)

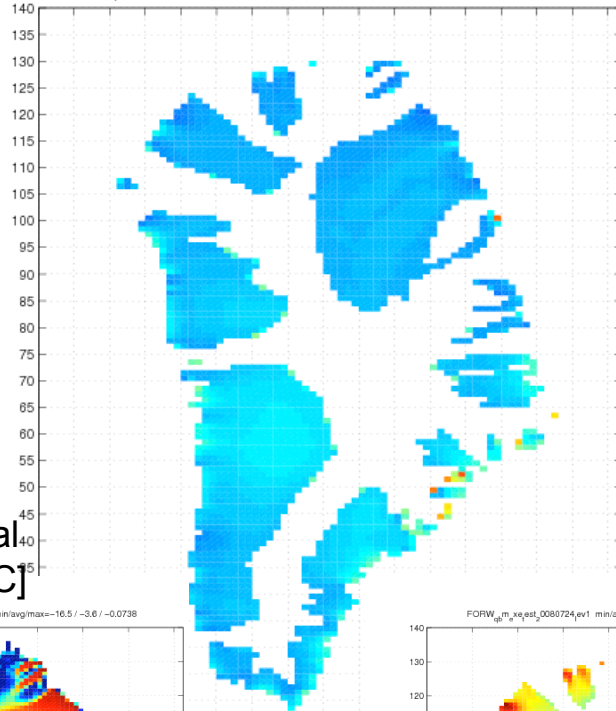




An adjunct of the ice sheet model SICOPOLIS

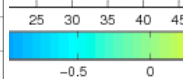
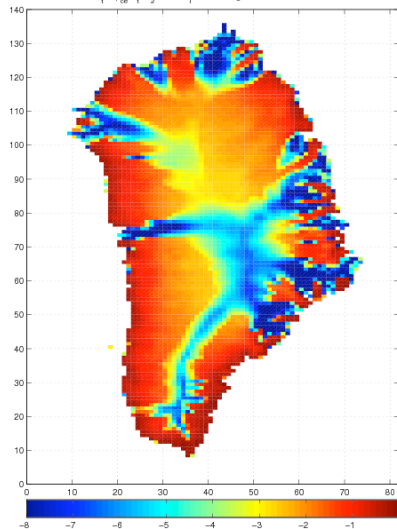
basal melt rate sensitivity

AD_qb_m_xe_est_0080724.ev1 min/avg/max=-1.21e+18 / -7.55e+17 / 1.25e+18

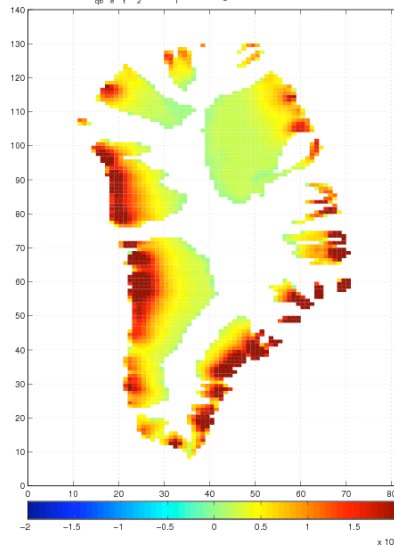


reference basal
temperature [°C]

FORW_empt_xe_est_0080724.ev1 min/avg/max=-16.5 / -3.6 / -0.0738



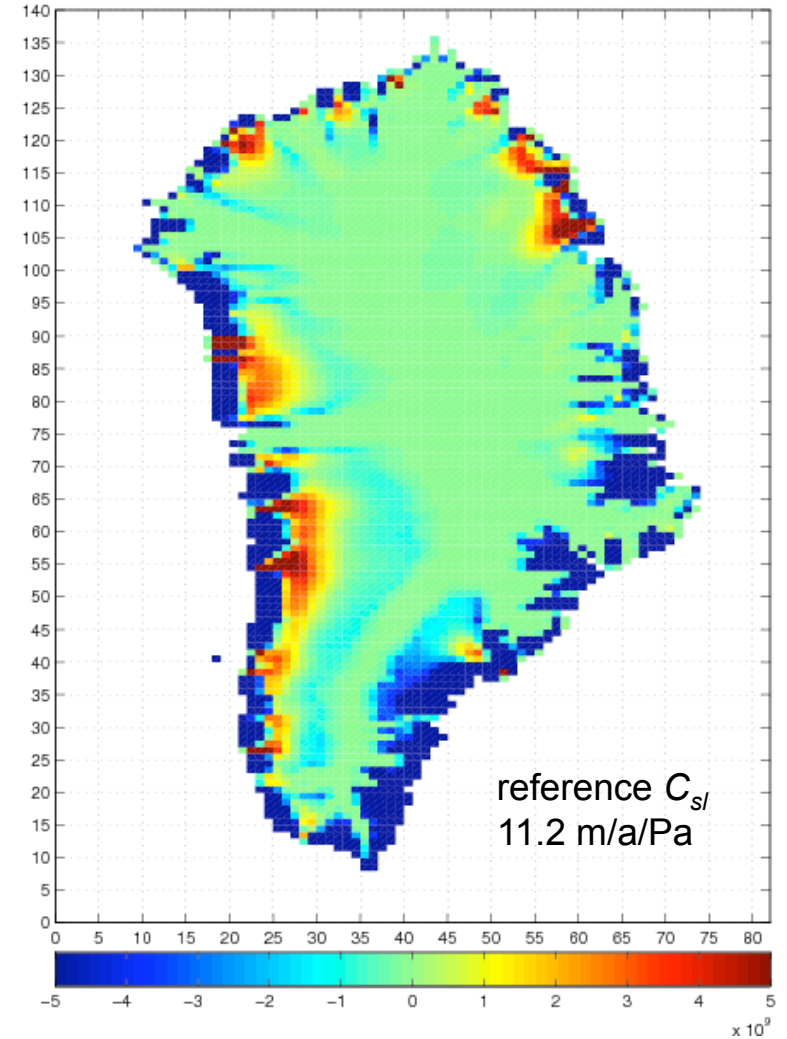
FORW_qb_m_xe_est_0080724.ev1 min/avg/max=5.8e-13 / 1.06e-09 / 1e-08



reference basal melt rate [kg/m²/s]

basal sliding sensitivity

AD_cs_lide_xe_est_0080724.ev1 min/avg/max=-3.63e+11 / -6.87e+09 / 4.07e+10



reference C_{sl}
11.2 m/a/Pa

